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Experimental study on the characteristics of secondary airflow device in a large enclosed space building

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ABSTRACT

Large space building using side wall nozzle air-conditioning system may result in poor ventilation effectiveness for positions out of the reach of primary supply air. A secondary airflow device is proposed to be applied in such system to improve the uniformity of temperature and velocity distribution in the occupied zone under cooling condition. The characteristics of the secondary airflow device, including central-line velocity decay and jet trajectory model were investigated through experiments to provide fundamental data for the system design. The indoor thermal environment parameters were measured and compared between with and without the secondary airflow device system in a large space factory workshop conditioned by side wall air supply nozzles. Experimental results with the secondary airflow device showed that the vertical thermal stratification height slightly changed, with lower air temperature in unoccupied zone and higher temperature in occupied zone comparing to the cases without secondary airflow device. At occupied level, air diffusion performance index (ADPI) significantly improved, while the percentage dissatisfied (PD) due to draught decreased in the occupied zone. Air velocity uniformity at occupied level also significantly increased. The results of this study provide an exemplary reference for the design of the air distribution system in large-space buildings.

1. Introduction

Building ventilation for large enclosures, such as factory workshop, music concert, transportation terminals and sports gymnasium, is of great challenge in HVAC system design. Due to a relatively greater floor-to-ceiling height comparing to a regular space in the building, vertical thermal stratification and partial air conditioning in the occupied zone at a lower height of such space have drawn substantial attention [1]. In practice, displacement ventilation can be used to condition occupied zone and leave unoccupied zone unconditioned. It is found that return position significantly affect vertical temperature gradient [2]. Displacement system working with radiant cooling floor shows 34% energy saving compared to traditional large space building ventilation system [3]. Traditionally, jet ventilation terminal devices are often located on sidewalls and close to the occupied zone to reduce energy consumption, creating a partially conditioned indoor environment [4–7]. Nevertheless, the relatively large span of these spaces still poses a major challenge on delivering enough amount of fresh air to the occupied space that is far from supply air terminals, which could result in non-uniformity of air temperature and velocity distribution and the decrease of thermal comfort level in such locations. Localized air terminals connected to supply air duct may not be applicable since they are suspended in the middle of the space, conflicting the functional requirement of the building. Stagnant air in such region will lack momentum to disperse and remove airborne contamination [8,9], as well as heat and humidity load [10].

Parking garages [11] and tunnels [12] apply induction fans in the ventilation system near the ceiling to solve this problem. In these systems, induction fans perform a secondary airflow to circulate indoor airflow and improve ventilation effectiveness. Such strategy proves efficacious and has been extensively discussed in many applications. For example, performance of induction fan jet applied in tunnel mainly depends on the interval of the fans and the distance between the tunnel wall and the fan [13], as well as inclined pitch angle [14]; it is found that the optimal pitch angle is 6° for free tunnel and 2–4° for tunnel with traffic jam [15]; induction fan can also be installed along tunnel side wall with certain angle to induce longitudinal airflow to enhance ventilation effectiveness [16]; the performance and efficiency of induction fan applied to car parks are significantly affected by their position

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[17] such as free and near-wall positioning and fan outlet deflector as well. Induction jet fan system is also much more efficient in thinning contaminant than traditional duct systems [18].

The induction fan system utilized in aforementioned occasions is a potential solution to large space building ventilation, as the extra momentum from induction fan acts as a driving force for heat and contaminant load removal in the location that regular airflow terminal barely reaches. However, the large enclosed space in buildings with both greater height or horizontal size, is essentially different from car parks or tunnels. Typical parking garage usually has similar floor-to-ceiling height as ordinary building but greater floor area, while traffic tunnels are characterized with much greater longitude distance with induction fans airflow relaying each other. In addition, air-conditioning system of a large space building relies on supply air terminals such as nozzles and diffusers to deliver primary conditioned air, but parking garage and traffic tunnel does not necessarily have well organized supply air, which can be exhaust resultant (for garage) or infiltration from opening (tunnel). For large space buildings, conditioned air supplied [19] by a regular air distributor, such as side-wall air supply nozzle, can be passed along to the induction fan system that performs as secondary airflow relay [20] to enhance the movement of indoor air near the occupied zone. The secondary airflow will help provide extra momentum [21] to the supplied air as well as help disperse and remove contaminant in occupied space.

In mechanism, parking garage and traffic tunnels are typically isothermal but air-conditioning systems has temperature difference between supply air and occupied zone. Successful application of induction fan in parking garage and tunnels does not necessarily compliant with large space building. In order to understand the mechanism and performance of such new system, a series of experimental tests are conducted by reconstructing a large factory workshop in Shanghai, China with the new system installed. Nozzles at the side wall are used to supply primarily conditioned air and induction fans in front of nozzles are installed as the secondary airflow relay to improve ventilation effectiveness of the workshop.

2. Experimental setup

2.1. Experiment facility

In order to systematically investigate the characteristics of secondary airflow device in a large enclosed space, a factory workshop, which was a typical large space building equipped with an air handling unit (AHU) to supply conditioned air through 8 side wall nozzles was tested. This building was a student machining training center located in the campus of University of Shanghai for Science and Technology, and all tests were conducted during August 2013. As shown in Fig. 1, the air handling unit room is attached to the experimental factory workshop. There are 2 rows of round nozzles, which are installed at the height of 8.2 m and 5.5 m, respectively, to supply conditioned air to this workshop. Air return is a single grille of 3 × 2 m (0.6 m above the floor) at the same side as the supply nozzles. Eight jet fans [22] in a row are located at 6 m in front of the primary air supply nozzles at the height of 5.1 m. As of the thermal property of building envelope, heat transfer coefficient of wall, roof and window are 2.05, 0.91 and 6.38 W/(m^2 k) respectively. As indicated by the compass, external walls are located at northwest and southwest direction with windows. The other two sides of the workshop are internal walls adjacent to unconditioned area of the factory.

In order to investigate the characteristics of the thermal environment created by different ventilation systems, indoor air temperature and velocity were measured in different representative locations. Pole A–I in Fig. 1 indicate the locations of the measurement points. An extra pole N is added to represent the center of the indoor space in front of the secondary jet fan. These points start from the height of 1.7 m with 1.0 m interval vertically. Point J–M are added right in front of the central jet fan at the height 1.7 m as well. Indoor air temperature was measured at all these points to investigate the vertical thermal stratification effect as well as horizontal temperature distribution, while air velocity values were measured only at the height of 1.7 m due to limited number of velocity sensors in this experiment, which was to represent the occupied zone in this workshop. The photograph of the tested ventilation system in the factory workshop is shown in Fig. 2.

Instruments used in the experiment and their technical specifications are listed in Table 1. Instruments used in the jet trajectory experiment include Vientiane anemometer SWP-NSR with a precision of ±0.05 m/s, KIMO-VT50 hot-wire anemometer with a precision of ±3% reading, ±0.06 m/s, HD2003 E + E for temperature and humidity measurement with a precision of ±0.2 °C and ±3%.

2.2. Jet characteristics of the secondary airflow device

The performance of jet fans (Fig. 1) as the secondary airflow device including the jet trajectory path and velocity decay in this ventilation system is critical for the system to create a certain indoor conditions of the built environment. Classical air jet theory to describe jet airflow penetration from free/confined slot may not be applicable since the device is axial fan instead of inlet slot, therefore fan blades may have significant impact on the outlet airflow character. It is possible that air jet trajectory from this type of secondary airflow device is quite different from what existing model describes.

Before installation of these fans in the system, a series of experiments to test the characteristics of the device were conducted in the factory workshop. Jet trajectory path can be quantified by visualization [23] as well as trajectory equation [24]. In this study, the jet trajectory was determined by finding out the maximum velocity position within the jet region predicted by the theoretical jet trajectory. As shown in Fig. 2(a), in the jet fan experiment, one single secondary airflow jet fan was put in an empty space at the height of 4.0 m, and 16.0 m off the front wall. It was assumed that horizontal direction along the jet was the x-direction and vertical direction was the y-axis starting from floor level. For non-isothermal jet test experiment, cold air was directly delivered to the device inlet by cooling fan. Jet air temperature difference was determined by ambient temperature subtract jet fan outlet air temperature.

As shown in Fig. 3, horizontally every 1000 mm in front of the jet fan, a vertical intersection A–A was selected. The points above and below the theoretical jet trajectory centerline were measured with 100 mm vertical intervals within each intersection A–A, and the point with the maximum velocity value would be considered as the actual jet center. Measurement points were placed near the theoretically calculated free air jet trajectory of round nozzle. There are different theoretical jet trajectory models in the literature [25], and the jet trajectory path model of Eq. (1) was obtained by reformatting Koestel [26] for horizontal jet fan put at the height of 4 m.

$$y = 4 - d \cdot Ar\left(\frac{x}{d}\right)^2\left(\frac{0.51ax}{d} + 0.35\right) \tag{1}$$

where y and x are the vertical and horizontal coordinates of the jet path in m; d is the nozzle diameter in m; Ar is Archimedes number of the cold jet; and a is the turbulent intensity equals to 0.076 for round nozzle in this case.

A new jet center line trajectory would be obtained from identifying the maximum velocity vertically and then the points on both sides horizontally were measured at 100 mm interval afterwards, and the maximum velocity position was used to revise the jet